

**Characterizing Diesel Exhaust Particulate Matter, Elemental, and Total Carbon
Concentrations During Snorkeling Operations of Los Angeles Class Submarines**

by

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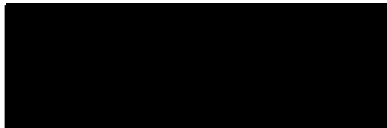
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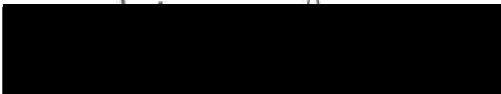
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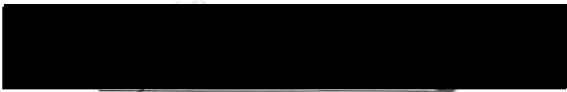
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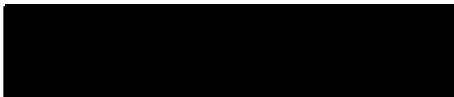
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DEDICATION

This thesis is dedicated to the brave men and women of the U.S. Navy Submarine Service. You are the battle hardened, steely-eyed warriors of the Silent Service who brave the cold dark depths of the world's oceans. It is you who are on the front lines of the invisible battlefield, protecting the nation from the unseen enemy. It is you who have dealt the decisive blows in battles past, present, and future. It is you who have made the ultimate sacrifice aboard USS Thresher and USS Scorpion and will remain on Eternal Patrol. It is you who consistently answer the call of duty and understand the rich heritage to which you proudly belong. The Dolphins you wear upon your uniform mark you forever as a 'Qualified Submariner'. I proudly wear those same Dolphins. Though, I am no longer in the Submarine Service, I am forever a Submariner. Thank you for your service!

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August 6, 2019

ABSTRACT

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2019

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Background: Personnel working in an operational environment on U.S. Navy Los Angeles Class Submarines may be exposed to Diesel Exhaust (DE) at concentrations higher than recommended occupational exposure limits while submarines operate the Emergency Diesel Engine (Snorkeling). Exposure to elevated levels DE has been linked to adverse health effects such as asthma, headaches, irritation of the nasal passage, and nausea. DE has been classified as a carcinogen by the International Agency for the Research of Cancer (IARC) due to a strong association between exposure to DE and the development of lung cancer.

The objective of this study was to characterize the concentrations of Diesel Exhaust Particulate Matter (PM_{10, 2.5, RESP}), Elemental Carbon (EC), and Total Carbon (TC) and to determine whether occupational exposure limits are exceeded during pier-side Snorkeling operations.

Methods: Area air sampling was conducted outside and inside three LA Class Submarines in Groton, CT, and Norfolk, VA. A total of 27 air particulate samples were collected in nine sampling zones, over 4-hour periods using SKC air sampling pumps and 37-mm quartz fiber filters in accordance with NIOSH Analytical Method 5040. Additional air sampling was conducted at the topside guard shack and in the Auxiliary Machinery Room using a direct reading aerosol monitor. EC concentrations were compared to Cal OSHA recommended threshold limit value (TLV) $20 \mu\text{g}/\text{m}^3$ as an 8-hr time weighted average (TWA). TC concentrations were compared to the Mining Safety and Health Administration (MSHA) permissible exposure limit (PEL) $160 \mu\text{g}/\text{m}^3$ as an 8-hr TWA. PM_{RESP} concentrations were compared to ACGIH, Particles Not Otherwise Specified (PNOS) TLV ($3,000 \mu\text{g}/\text{m}^3$).

Results: Approximately 22% of EC and 44% of TC samples collected at topside and pier-side locations on Submarine 1 exceeded the Cal OSHA TLV and MSHA PEL. Mean EC/TC concentrations were highest within a 50-feet of the exhaust ports: 17 and $309 \mu\text{g}/\text{m}^3$ respectively. 100% of the EC samples collected on Submarine 2 were below the limit of detection (LOD) of the analytical method. Mean EC concentrations on Submarine 3 in the forward compartment upper, middle, and lower level were 18, 24, and $28 \mu\text{g}/\text{m}^3$ respectively. Mean TC concentrations were 467, 600, and $787 \mu\text{g}/\text{m}^3$ respectively. Approximately 67% of EC and 100% of TC sample locations in the forward compartment inside Submarine 3 exceeded the Cal OSHA TLV and MSHA PEL. EC/TC concentrations were highest in the lower level of the submarine. PM_{RESP} outside of Submarine 1 exceeded ACGIH PNOS TLV.

Conclusion: Results of this study suggest that PM, EC, and TC levels may exceed recommended exposure limits while a Los Angeles Class submarine conducts snorkeling operations both inside and outside the submarine. TC concentrations were higher inside the submarine than in areas outside the submarine. A combination of administrative and engineering controls should be considered to reduce exposure to DE during snorkeling operations. Future studies should collect samples on Virginia and Ohio Class U.S. submarines.

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CHAPTER 1: Introduction

STATEMENT OF PURPOSE

The purpose of this study was to characterize the concentrations of diesel exhaust particulate matter (PM₁₀, PM_{2.5}, PM_{RESP}), elemental carbon (EC), and total carbon (TC) and to determine whether occupational exposure limits are exceeded during snorkeling operations.

BACKGROUND

Diesel engine exhaust emissions from the Emergency Diesel Engine on U.S. Los Angeles class submarines may present a health hazard to U.S. Navy personnel working on board and outside during snorkeling operations. Diesel exhaust (DE) is a complex mixture of combustion byproducts to include gases and aerosols in organic and inorganic form. Constituents of DE include carbon, carbon monoxide (CO), nitrogen dioxide (NO₂), sulfur dioxide (SO₂), trace levels of metals, benzene, formaldehyde, acrolein, and other hydrocarbons. These constituents are emitted at varying rates and concentrations depending on the type of diesel engine, efficiency of the diesel engine, load and speed of the engine, composition of the diesel fuel, and whether emission control equipment is installed. Sampling for carbon, CO, NO₂, SO₂, metals, benzene, formaldehyde, acrolein, and other hydrocarbons contained in diesel exhaust is challenging since sampling methods vary with each contaminant and may not accurately reflect true DE concentrations. Additionally, the presence or absence of any of these constituents, individually, may not be reflective of total DE concentrations. As a result, The National Institute for Occupational Safety and Health (NIOSH) recommends sampling for

elemental carbon (EC) as a surrogate of exposure because diesel particulate matter is predominantly (typically greater than 80%) carbon (5). EC, black carbon, and carbon black are often used interchangeably to refer to the light absorbing core at the center of the DE particle (Figure 1). EC cores are usually coated with organic carbon (OC) compounds and small amounts of trace elements produced during the combustion of diesel fuel as illustrated in Figure 1. Total carbon (TC) is the sum of all the organic compounds present in a DE particulate (Figure 1). For that reason, total carbon (TC) has also been used as a surrogate of exposure to DE as it can be used as a measure of all of carbon compounds present in DE.

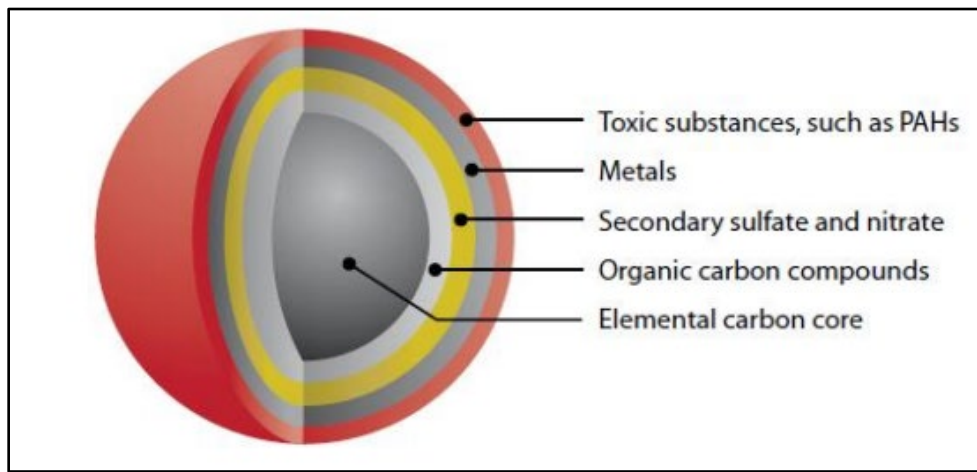


Figure 1: Composition of Diesel Particle (1)

Occupational exposure limits related to DE are limited in the United States. The Occupational Safety and Health Administration (OSHA) has not established a federal permissible exposure limit (PEL) for DE. The Mine Safety and Health Administration (MSHA) has set a PEL of $160 \mu\text{g}/\text{m}^3$ for total carbon (TC) as an 8-hour time-weighted average for miners working in underground metal and nonmetal mines. The MSHA PEL was used in this study as a point of comparison for TC concentrations due to the lack of

availability of occupational exposure limits related to DE. The American Conference of Governmental Industrial Hygienists (ACGIH) had proposed setting a threshold limit value (TLV) for EC at $20 \mu\text{g}/\text{m}^3$, in its Notice of Intended Changes, in 2001. The ACGIH recommended TLV was rescinded in 2003 and placed on the *Under Study* list. California OSHA adopted the ACGIH's recommendation for EC (6). The Cal OSHA recommended exposure limit for EC was used as a point of reference for comparison to mean concentrations collected from each submarine during this study.

Adverse health effects of DE are predominantly linked to its particulate fraction. The shape, size, and density of DE particulates determine the particle behavior. The larger particles in DE undergo sedimentation and impaction when inhaled. Aerosol particles greater than $10 \mu\text{m}$ are unable to navigate the sharp turns of the nasal passages and are deposited by impaction in the nasopharynx region of the respiratory system. Fine particulates ($2.5 \mu\text{m}$ and smaller) can penetrate deep within the lungs, beyond the terminal bronchioles, and into the gas exchange region of the lung. Previous studies have found that long term exposure to coarse (greater than $2.5 \mu\text{m}$) and fine particulates are associated with an increased risk of morbidity and mortality (26) (30) (29). PM_{10} , $\text{PM}_{2.5}$, and PM_{RESP} concentrations were used in this study to characterize DE particulate matter during snorkeling operations at various internal and external locations. Concentrations were compared to ACGIH Particles Not Otherwise Specified TLVs (2).

DESCRIPTION OF THE SUBMARINE DIESEL ENGINE

All classes of modern United States submarines have emergency diesel engines. The Submarine Emergency Diesel Engine is used during emergency situations, such as loss of main propulsion (nuclear power), generation of electrical power, or provision of

emergency ventilation. Additionally, these engines are routinely operated in preparation for: underway operations, quarterly performance analysis, shipboard personnel qualification, monthly maintenance and training exercises. Annually, these engines are operated in excess of 60 hours on average (10). Fresh air, needed to complete the combustion of the diesel fuel, is provided to the engine through the submarine's air induction system, while exhaust systems discharge exhaust and combustion by-products overboard. Seawater is injected at a rate of about 11.5 gallons per minute into the exhaust prior to venting overboard into the atmosphere (10). The injected water serves two purposes; cooling water for the ductwork and reducing exhaust ducting corrosion caused by high temperatures (10).

The approximate air exhaust flow rate of the Submarine Emergency Diesel Engine on an LA class submarine is 6,500 cubic feet per minute (10). For reference, a 2017 Dodge Ram with a 6.7L Cummins diesel engine, has an air exhaust flow rate of about 1,250 cubic feet per minute (8). On-road heavy diesel equipment and vehicles often have particle filtration devices installed, in compliance with EPA standards, intended to reduce environmental concentrations of DE particulate matter. U.S. submarines are not required to have these pollution control devices installed. The result is an unfiltered exhaust plume containing a mixture of combustion byproducts that could pose a health risk while the submarine snorkels pier-side

Submarines can operate their diesel engine while on the surface of the water, while submerged at sea, or while pier-side. This operation is commonly referred to as "snorkeling". To date, limited data has been collected to characterize the concentrations of DE during snorkeling operations while pier-side or while the submarine is submerged

at sea. During at sea operations, the Central Atmosphere Monitoring System (CAMS), provides real time monitoring of oxygen, carbon dioxide, hydrogen, water vapor, nitrogen, carbon monoxide, and refrigerant gases while the submarine is submerged. The CAMS cannot, however, monitor DE constituents at sea and are not operated while the submarine is in-port. Fresh air is provided to the submarine using centrifugal fans which discharge air into the fan room for distribution throughout the ship (23). Since the diesel exhaust port is in close proximity of the Snorkel Induction Mast, through which fresh air is supplied, some diesel exhaust may infiltrate the ship during snorkeling operations, depending on wind speed and direction (10). Figure 2 is a picture of the sail of a Los Angeles Class submarine, showing how close the diesel exhaust ports are relative to the Snorkel Induction Mast. A 2008 observational study published by Duplessis et al., described a case where diesel exhaust was circulated throughout a US submarine for 9-hours while the vessel operated the diesel generator during pier-side drills (9). Thirty eight crewmembers required corticosteroid treatment and observation for the development of Reactive Airway Dysfunction Syndrome (RADS) due to acute exposure to DE (9).



Figure 2: Sail configuration of a LA Class Submarine (17)

Security watch standers and ship's crew may be exposed to DE outside the submarine during snorkeling operations. Two security watch standers, the 'Petty Officer of the Watch' and 'Topside Sentry', are posted topside under normal force protection conditions to control access to the submarine. The Topside Sentry 'roves' the topside and pier-side footprint of the submarine continuously during their security watch period. The Petty Officer of the Watch controls access to the submarine from the Guard Shack, near the forward egress brow. Watch rotations usually last from four to six hours. The guard shack is usually directly adjacent to the diesel exhaust vents, depending on pier configuration (Figure 3). Other crew members may spend time topside doing maintenance, painting, and on/off-loading items from the submarine for minutes to hours at a time. Additionally, contractors and other personnel conducting maintenance activities may spend extended periods of time topside during snorkeling operations.



Figure 3: Pier-Side Security Guard Shack

Pier-side, particulate concentrations may approach or exceed MSHA 8-hr PEL ($160 \mu\text{g}/\text{m}^3$) and Cal OSHA recommended 8-hr TLV ($20 \mu\text{g}/\text{m}^3$) during snorkeling operations. Average particulate concentration levels of $112 \mu\text{g}/\text{m}^3$ and $118 \mu\text{g}/\text{m}^3$ while Australian submarines conducted snorkeling operations were reported in a study by Gan et al. (12). Changes in operating conditions, such as fluctuations in electrical load may affect levels of DE emissions (19). A study conducted by McDonald et al. demonstrated that exhaust produced under high load (approximately 100 percent capacity) had higher concentrations of elemental carbon than produced at partial loads (approximately 55 percent capacity) (19). This study also demonstrated an inverse relationship between engine operating load capacity and OC/EC concentrations. At partial load capacity the OC/EC ratio was approximately 90:10, while at full load capacity the OC/EC ratio was

approximately 10:90 (19). High concentrations of EC are indicative of the complete combustion of diesel fuel. High concentrations of OC are indicative of the presence of uncombusted diesel fuel and lubricating oils.

RESEARCH QUESTIONS, HYPOTHESES, AND SPECIFIC AIMS

Research Question #1

Do EC and TC concentrations outside and inside the hull of a submarine exceed exposure limits during snorkeling operations?

Hypothesis #1

EC and TC concentrations outside and inside the hull of a submarine do not exceed exposure limits during snorkeling operations.

Specific Aims

1. Perform area sampling using air sampling pumps and 37 mm quartz fiber filters.
2. Compare EC concentrations to Cal OSHA TLV.
3. Compare TC concentrations to MSHA PEL.

Research Question #2

Are EC/TC concentrations affected by distance from the source outside and inside the submarine during snorkeling operations?

Hypothesis #2

EC/TC concentrations are not affected by distance from the source outside the submarine during snorkeling operations.

Specific Aims

1. Perform area sampling using air sampling pumps stationed at nine locations outside the submarine.
2. Perform area sampling using air sampling pumps stationed at nine locations inside the submarine.
3. Compare EC/TC concentrations based on sample location.

Research Question #3

Is there a difference between mean EC/TC concentrations inside the submarine forward compartment Upper Level, Middle Level and Lower Level during snorkeling operations?

Hypothesis #3

There is no difference between mean EC/TC concentrations inside the submarine forward compartment Upper Level, Middle Level and Lower Level during snorkeling operations.

Specific Aims

1. Perform area sampling using air sampling pumps stationed at nine forward compartment locations inside the submarine.
2. Compare mean EC/TC concentrations on the Upper, Middle, and Lower levels of the submarine forward compartment.

Research Question #4

Do PM_{10} , $PM_{2.5}$, PM_{RESP} concentrations outside and inside the hull of a submarine exceed recommended exposure limits while a Los Angeles Class submarine conducts snorkeling operations?

Hypothesis #4

Do PM₁₀, PM_{2.5}, PM_{RESP} concentrations outside and inside the hull of a submarine do not exceed recommended exposure limits while a Los Angeles Class submarine conducts snorkeling operations.

Specific Aims

1. Perform area sampling using size selective DRI.
2. Compare PM_{RESP} concentrations to ACGIH Particles Not Otherwise Specified recommended limit.
3. Describe PM₁₀ and PM_{2.5} concentrations.

CHAPTER 2: Literature Review

DIESEL EXHAUST REGULATIONS

Diesel exhaust is a complex mixture of gases, combustion byproducts, unspent fuel, polycyclic aromatic hydrocarbons (PAHs), and carbon-based particulates as well as trace levels of heavy metals such as iron, zinc and copper. Many of the components contained in diesel exhaust such as carbon monoxide, and sulfur dioxide are regulated by organizations such as OSHA, EPA, Department of Defense, and MSHA. Since the list of regulations concerning the compounds and elements contained within DE is extensive, regulations and recommendations governing recommended DE surrogates of exposure were used in this study as points of comparison.

Navy Industrial Hygiene Field Operations Manual (IHFOM)

The IHFOM is a manual published by the Navy and Marine Corp Public Health Center. The purpose of the manual is to provide internal working guidance for the practice of industrial hygiene (IH) to Bureau of Medicine and Surgery (BUMED) IH field personnel. Chapter 4 of the IHFOM instructs IH personnel to evaluate all recognized occupational health risks and provide professional recommendations to minimize or eliminate those risks (24). The Navy shall use the following hierarchy of OELs for chemicals:

1. DOD or Navy developed or adopted standards.
2. OSHA Permissible Exposure Limits
3. ACGIH TLVs where OSHA PELs are not available. When the OSHA PEL is less stringent, ACGIH TLVs shall be included in reports of data to supplement the OSHA PEL and aid in the risk management process.

4. Nationally recognized IH best practices shall be used to supplement the OEL hierarchy. Professional judgement should be used to recommend OEL guidelines, when appropriate, to aid the risk management process in a given situation. Sources include but are not limited to: Cal OSHA PELs, NIOSH recommended exposure limits, and Occupational Alliance for Risk Science (OARS) Workplace Environmental Exposure Levels (WEELs) (24).

For many U.S. Navy processes, exposure monitoring opportunities may be infrequent due to operational requirements or too variable across multiple platforms of naval vessels. In these cases, the IHFOM instructs the IH professional to exercise professional judgement, after considering the available information and make an exposure assessment with a well-documented rationale (24).

MSHA

MSHA uses TC as a surrogate of exposure to DE due to interferences which may make measured EC concentrations unreliable. MSHA 30 CFR Part 57 implemented a 8-hr PEL for TC of 160 $\mu\text{g}/\text{m}^3$ in 2008 (20). The 160 $\mu\text{g}/\text{m}^3$ TC limit was initially promulgated in the 2001 final rule, *Diesel Particulate Matter Exposure of Underground Metal and Nonmetal Miners*, which was published in the Federal Register in January 2001 and amended in 2006 (20). Under the amended 2006 rule, MSHA intended to issue a proposed rule to convert the 160 $\mu\text{g}/\text{m}^3$ TC PEL to a comparable EC PEL prior to the 2008 effective date, provided sufficient scientific data were available to support it. The TC to EC conversion would be accomplished by using a universal conversion factor. MSHA decided not to issue a uniform conversion factor based on the assessment that

there is insufficient evidence suggesting an appropriate conversion factor regarding the relationship between TC and EC at concentrations as low as 160 $\mu\text{g}/\text{m}^3$ TC (20).

ACGIH

ACGIH first proposed a 150 $\mu\text{g}/\text{m}^3$ TLV in its Notice of Intended Changes (NIC) for 1995 (5). EC was selected as a surrogate of exposure to DE since it can be accurately measured at low concentrations (about 2 $\mu\text{g}/\text{m}^3$). In 1999 the ACGIH further reduced the TLV for DE to 50 $\mu\text{g}/\text{m}^3$ and recommended monitoring for TC as a surrogate of exposure to DE. Two years later, in its NIC, ACGIH recommended further reductions to 20 $\mu\text{g}/\text{m}^3$ and recommended monitoring EC as a surrogate of DE exposure. However, in 2003, ACGIH withdrew the proposed recommendations and placed it on their '*Chemical Substances and Other Issues Under Study*' list. DE is currently on ACGIH's 2019 *Chemical Substances and Other Issues Under Study* list (3). Limits for particles not otherwise specified (PNOS) are published in the ACGIH's 2017 *Threshold Limit Values & Biological Exposure Indices* book (2). ACGIH recommends that airborne concentrations should be kept below 3 mg/m^3 for respirable particles (smaller than 4 μm), and 10 mg/m^3 for inhalable particles (smaller than 100 μm), until such time as a TLV is set for a particular substance (2).

OSHA

OSHA has not established a standard for DE as a unique occupational hazard, though specific components of DE (CO, SO₂, PAHs, etc.) do have occupational exposure limits. The General Duty Clause, as set forth by the OSH Act of 1970, states that "each employer shall furnish to each employee a place of employment which are free from

recognized hazards that are causing or are likely to cause death or serious physical harm to their employees” (36).

California OSHA

The California Department of Public Health, Occupational Health Branch (Cal OSHA) recommends exposure to DE levels (EC) be kept below 20 $\mu\text{g}/\text{m}^3$ in the workplace (6).

Human Health Effects of DE

In 2012, the International Agency for Research on Cancer (IARC) reclassified diesel exhaust (DE) from Group 2A, *Possibly carcinogenic to humans*, to Group 1, *Carcinogenic to humans*. The reclassification was based on sufficient evidence that DE exposure is associated with an increased risk of lung cancer and the existence of a positive association between exposure to DE and cancer of the urinary bladder (16). Several studies have demonstrated associations between exposure to fine particulates (PM_{10} or smaller) from DE and lung cancer and an increase of respiratory morbidity and mortality. Fine particulates from DE can penetrate deeply into the lungs and stay for long periods of time before being expelled or metabolized. Additionally, these particulates have been demonstrated to induce inflammatory reactions within the airways.

Short term exposures to DE can cause dizziness, coughing, shortness of breath, eye, nose, and throat irritation, headaches, and pulmonary function change. Long term exposure to DE has been linked to increased risk of cancer, asthma, and death.

Vermeulen et al. estimated, assuming an average exposure of 0.8 $\mu\text{g}/\text{m}^3$ over 80 years, that there are 21 excess lung cancer deaths per 10,000 individuals from environmental exposures to DE annually (28). Vermeulen et al. also estimated a range of 17, 200, and

689 per 10,000 excess lung cancer deaths for occupational exposures to 1, 10, and 25 $\mu\text{g}/\text{m}^3$ EC, respectively of at least 45 years (28). Additionally, Vermeulen et al. estimated that 1.3% and 4.8% of annual lung cancer deaths at 70 years of age in the United States and the United Kingdom, respectively, are due to past occupational and environmental DE exposures (28).

A study conducted by Takizawa et al., observed the effect of diesel exhaust particulates on the production of inflammatory cytokines and mediators including IL-8 and granulocyte macrophage colony stimulating factor (GM-CSF) by human airway epithelial cells in vitro (31). The results of this study demonstrated that short term exposure to diesel exhaust particulate induced an acute inflammatory response and showed a time and dose dependent stimulatory effect on GM-CSF and IL-8 release by human bronchial epithelial cells.

A study conducted by Salvi et al., demonstrated that at high ambient concentrations, acute short-term DE exposure produces a well-defined and marked systemic and pulmonary inflammatory response in healthy human volunteers (29). Fifteen healthy human volunteers were exposed to diluted DE under controlled conditions for one hour while conducting intermittent exercise (29). Participants displayed a significant pulmonary and systemic inflammatory response within the lungs following exposure. These findings suggest that acute exposure to high levels of DE can induce rapid inflammation within the lungs.

Mudway et al., investigated whether breathing high concentrations of DE induces pulmonary inflammation, bronchoconstriction, increased airway reactivity, and oxidative stress in healthy subjects (21). Researchers exposed 25 healthy human volunteers to DE

PM₁₀ at a concentration of 100 µg/m³ for two hours in an exposure chamber. Self-reported symptoms included low-level nasal and throat irritation reported by 50 percent of the participants, development of mild headaches by 36 percent, and onset of mild nausea within the first hour of DE exposure by 16 percent of the participants (21). The findings of this study suggest that the antioxidant network at the air–lung interface in healthy subjects may be inadequate at concentrations often experienced in occupational settings (21).

A retrospective cohort study of trucking company workers was conducted to assess the association of exposure to diesel engine exhaust and lung cancer mortality. Researchers obtained the health records of 31,135 male workers above the age of 40, employed for at least one year in the unionized U.S. trucking industry from 1985 through 2000 (13). Adjusting for age and a healthy-worker survivor effect, lung cancer hazard ratios (HR) were elevated in long haul drivers, pickup and delivery drivers, and dock workers (HR: 1.15, 1.19, and 1.30 respectively) (13). Workers within these jobs have regular exposure to DE. Mortality risk increased linearly with years of employment and was similar across job categories despite different patterns of exhaust-related particulate matter from diesel trucks, city and highway traffic, and loading dock operations (13). This study concluded that workers within this industry who may have had regular occupational exposure to DE and other vehicle exhaust have an elevated risk of lung cancer with increasing years of work.

Hansen et al., conducted a retrospective cohort study which investigated the possible relationship between occupation exposure to DE and cancer risk among Danish truck drivers (15). This study identified a cohort of 14,225 truck drivers as well as a

control group of 43,024 blue collar laborers, and followed them for a ten year period (1970 – 1980) (15). The study showed an increased mortality for lung cancer, cancer of the bronchus, and laryngeal cancer among the studied group. The findings of this study indicate an increased risk of respiratory cancer and multiple myeloma among truck drivers who were exposed to DE (15).

ANIMAL STUDIES

Many studies have been conducted using different species of animals to evaluate the potential for carcinogenic effects from exposure to whole DE and to its components. Inhalation studies conducted using rats have demonstrated that DE can have carcinogenic effects and cause tumors. A study conducted by Nikula et al. chronically exposed F344 male and female rats to diluted DE for 16 hours per day, 5 days per week at target particle concentrations (2.5 mg/m^3 or 6.5 mg/m^3) to explore the effect of DE associated organic compounds in the formation lung tumors (26). In general, DE caused dose-related, nonneoplastic lesions as well as increases in the incidences and prevalence of malignant and benign lung neoplasms in the female rats (26).

Another study demonstrated the link between exposure to DE and changes in cardiac functions among rats susceptible to hypertensive heart failure (7). The findings demonstrated that acute exposures to DE can trigger immediate cardiovascular responses in the rat to include decreased blood pressure, increased heart rate variability, altered repolarization, and atrioventricular block arrhythmia (7).

Win-Shwe et al., conducted a study on the relationship between prolonged exposure (13 weeks) to nanoparticle-rich DE and decreases in cognitive ability and neurological effects in mice (37). This study found that the mice exposed to high

concentrations of nanoparticle-rich DE could not discriminate between a familiar object and a novel object, accompanied by a disturbance in the expressions of genes related to glutamate transmission in the hippocampus (37). Win-Shwe et al., also observed a tendency for prominent microglia activation in exposed mice which may induce neuroinflammation by producing proinflammatory cytokines, leading to further neurotoxicity (37). The findings suggest that subchronic exposure to high to DE may impair cognitive ability in mice.

A study conducted by McDonald et al., investigated the influence of diesel engine workload on selected responses: oxidative stress, inflammatory potential, susceptibility to lung infection, alterations in heart rate, and heart rate abnormalities (19). McDonald et al., demonstrated that markers of inflammation was significantly upregulated under both high and low load conditions (19). Mice exposed to high engine loads had decreased clearance of respiratory syncytial virus (RSV), when compared to control groups, suggesting that DE affected the ability of mice to fight respiratory infection (19). A significant reduction in heart rate compared to baseline was also observed among mice exposed to DE produced under high engine load (19). These findings suggest the intensity of inflammation of the airways and susceptibility to infection may be determined by diesel engine operating load.

OCCUPATIONAL EXPOSURE TO DE

Diesel engines are widely used across different industries around the world in both on and off-road applications. Industries which commonly use diesel engines include mining, construction, transportation, and railroads. Diesel engines are also used in the maritime environment on large naval vessels and on submarines of the United States and

in international navies. Exposure to DE is therefore highest among these industries due to the common frequency in which workers come into proximity to large diesel engines.

Mining and Hydraulic Fracturing

Pronk et al., conducted a literature review of occupational exposure to DE aimed at providing an overview of personal exposure levels to DE as reported in published literature related to various industries. Of the nearly 300 papers reviewed, the highest concentrations of DE exposure surrogates were observed in studies of underground mine exposure. The authors of the literature review looked at 18 different studies which characterized EC and particulate matter personal exposures in metal, non-metal, and coal mines across different job categories. Reported personal exposure EC concentrations were highest for underground production workers (mean: 148 – 658 $\mu\text{g}/\text{m}^3$) and lower for underground maintenance workers (mean: 53 – 144 $\mu\text{g}/\text{m}^3$) and underground unspecified and surface workers (mean: 13 – 66 $\mu\text{g}/\text{m}^3$) (27). The highest levels for PM_{Resp} were also reported for underground mining (mean: 710 – 3637 $\mu\text{g}/\text{m}^3$) and lowest for underground maintenance and (mean: 556 – 881 $\mu\text{g}/\text{m}^3$) (27).

Esswein et al., measured EC concentration from diesel powered equipment utilized in hydraulic fracturing operations in four states over a four-year period. Fifty-five area samples were collected during the study period. The mean area concentration observed in this study was 17 $\mu\text{g}/\text{m}^3$ (11).

Transportation

Pronk et al., observed EC personal exposure levels in the railroad industry published in three studies. The highest EC levels were reported for railroad maintenance workers (mean: 39 $\mu\text{g}/\text{m}^3$) (27). Levels for PM_{Resp} in these three studies were higher for

maintenance workers (mean: 196 $\mu\text{g}/\text{m}^3$) than for train crew members (mean: 126 $\mu\text{g}/\text{m}^3$) (27).

Groves et al., conducted a survey of exposure to DE in the workplace of forty job sites. EC and TC area sample concentrations of 84 and 176 $\mu\text{g}/\text{m}^3$ (geometric mean) from 155 area samples where forklift drivers worked were observed (14). EC and TC area sample concentrations of 32 and 100 $\mu\text{g}/\text{m}^3$ (geometric mean), from sixty-one area samples, were observed in a bus repair depot (14). In that same survey, EC and TC area concentrations were 35 and 89 $\mu\text{g}/\text{m}^3$ (geometric mean) in an ambulance depot (14).

Maritime

Groves et al., observed EC and TC area concentrations of 25 and 70 $\mu\text{g}/\text{m}^3$ (geometric mean) from area samples taken in work areas on vehicle transport ferries (14). Gan et al., conducted a study aimed at characterizing DE concentrations inside Australian submarines. Area samples collected inside two submarines for 24-hours measured EC concentrations ranging from 4 – 40 $\mu\text{g}/\text{m}^3$. EC and TC area samples collected outside the submarine measured 21 and 112 $\mu\text{g}/\text{m}^3$, respectively.

CHAPTER 3: Materials and Methods

MATERIALS

Materials used in this study for area sampling included:

- DustTrak™ DRX Aerosol Monitor 8534 (TSI Inc, Shoreview MN),
- AirChek® XR5000 air sampling pumps (Omega Specialty Division, SKC™ Inc., Eighty-Four, PA)
- 37 mm Quartz Fiber Filters (Maxxam Laboratories, Novi MI)
- 52-inch lightweight aluminum tripods
- Mesa Labs Defender 510 Medium Flow Primary Calibrator (Mesa Laboratories Inc, Butler, NJ)
- Kestrel 4000 Pocket Wind Meter (Kestrel Instruments, Boothwyn, PA).

METHODS

Submarine Selection

Convenience sampling of Los Angeles class submarines conducting snorkeling operations for a minimum of 4 hours, pier side, in Groton CT and Norfolk VA during July 2018 and March 2019, respectively, allowed the opportunity to gather exposure data used in this research. Air sampling was conducted on three submarines: Submarine 1 located at Submarine Base New London, Groton, CT in July 2018, Submarine 2 located in Norfolk Naval Shipyard in Norfolk, VA in March 2019, and Submarine 3 at Naval Station Norfolk in Norfolk, VA in March 2019. Each submarine was deidentified of ship name and hull number in accordance with standard U.S. Naval operational security practices. Submarine scheduling and sampling availability was coordinated through representatives at Naval Submarine Support Center (NSSC) New London, Commander

Submarine Force Atlantic (COMSUBLANT), shipboard medical department representatives, Naval Sea Systems Command (NAVSEA), and representatives at Code 106 at Norfolk Naval Shipyard. The Chain of Command for each submarine was briefed on the purpose of the sampling prior to commencement.

Sample Collection

Air samples were collected using closed-face 37-mm quartz fiber filters in 3-piece cassettes connected to 50-inch length, ¼ inch Tygon tubing and AirChek XR5000 pumps set at a flow rate of 4 L/min. Air sampling media was mounted at a height of 50 inches on aluminum tripods. Figure 4 is a picture of the air sampling configuration.

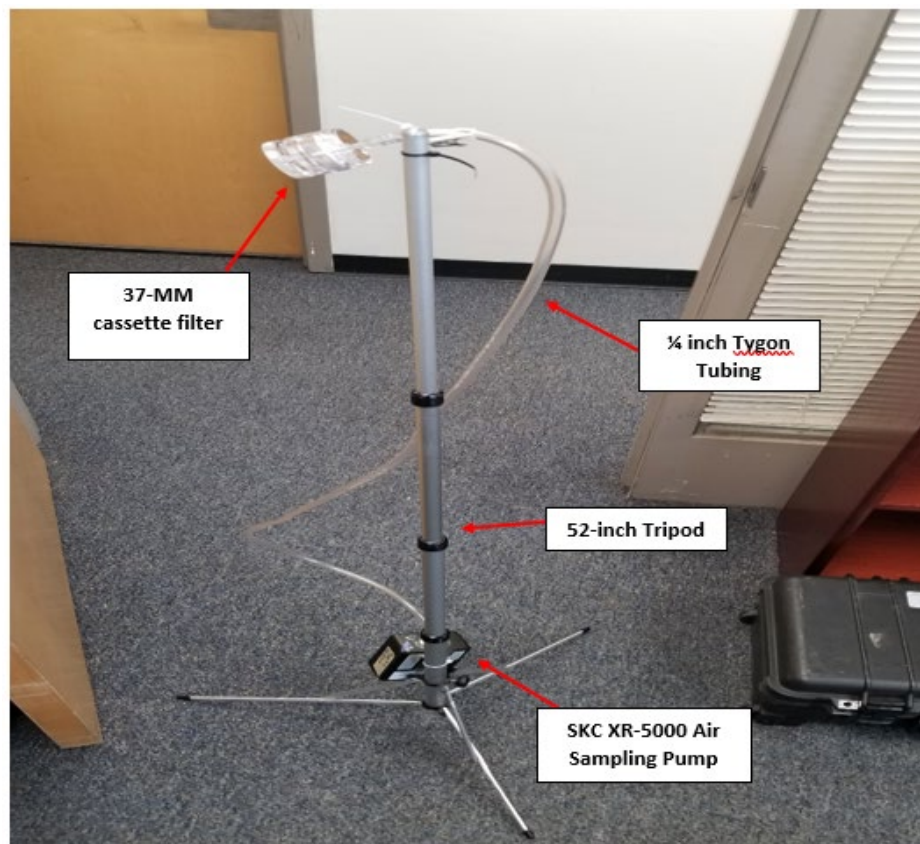


Figure 4: Air Sampling pump mounted on 52-inch aluminum tripod

Air sampling locations for Submarine 1 and 2 were selected in locations where security watch personnel and other ship crew members may stand outside of the submarine. Figure 5 is an overhead depiction of a standard pier-side configuration of a U.S. submarine, with sample locations labeled. Eight tripod mounted sample pumps were placed atop the submarine and on the pier (Figure 5). A ninth tripod mounted sample pump was placed inside the Guard Shack. Filter sample analysis was performed by Maxxam Analytics (Novi, MI), an American Industrial Hygiene Association (AIHA) accredited laboratory using NIOSH 5040 Method.

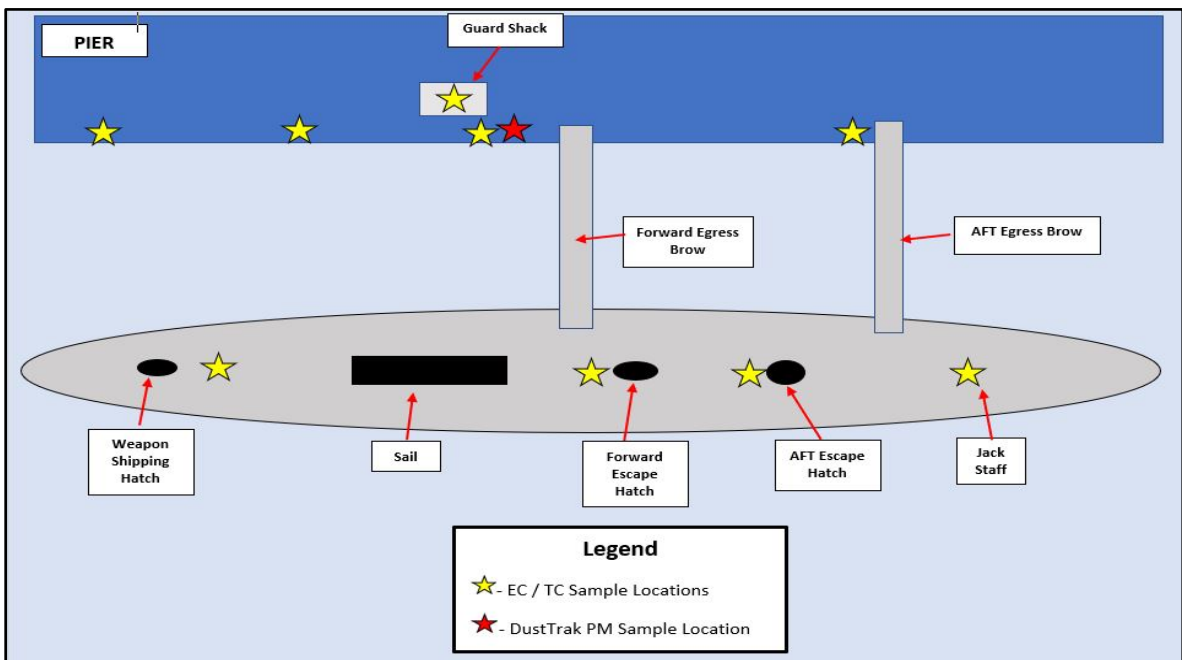


Figure 5: Aerial Depiction of a Submarine pier-side with sample locations labeled

PM₁₀, PM_{2.5}, and PM_{RESP} mass concentrations were monitored using a DustTrak DRX 8534 (TSI Inc, Shoreview MN) direct reading aerosol monitor, placed outside the Guard Shack (Figure 4). Wind speed and direction, temperature, humidity and barometric pressure measurements were taken with the Kestrel 4000 Pocket wind meter prior to commencement of air sampling. Navy Marine Corp Public Health Center

(NMCPHC) form 5100/13, Industrial Hygiene air Sample Survey Form, was used to log sample data to include location, sample duration, pump flow rates, environmental conditions, and total sample volume.

Area air sampling was conducted inside of Submarine 3. Nine air sample locations were selected in the upper, middle and lower levels of the Forward Compartment. Each area was representative of workspace or bunk room area where crewmembers work, eat, and sleep. EC/TC was sampled in the following forward compartment spaces: Navigation Center, Control Room, Combat Systems Equipment Space (CSES), Crew Mess, Middle Level Passageway, Forward Crew Berthing, Auxiliary Machinery Room (AMR), Lower Level Passageway, and Torpedo Room (Figure 6). Additionally, PM mass concentrations were monitored inside the Diesel Operator's Booth, located in the AMR, using a DustTrak DRX 8534.

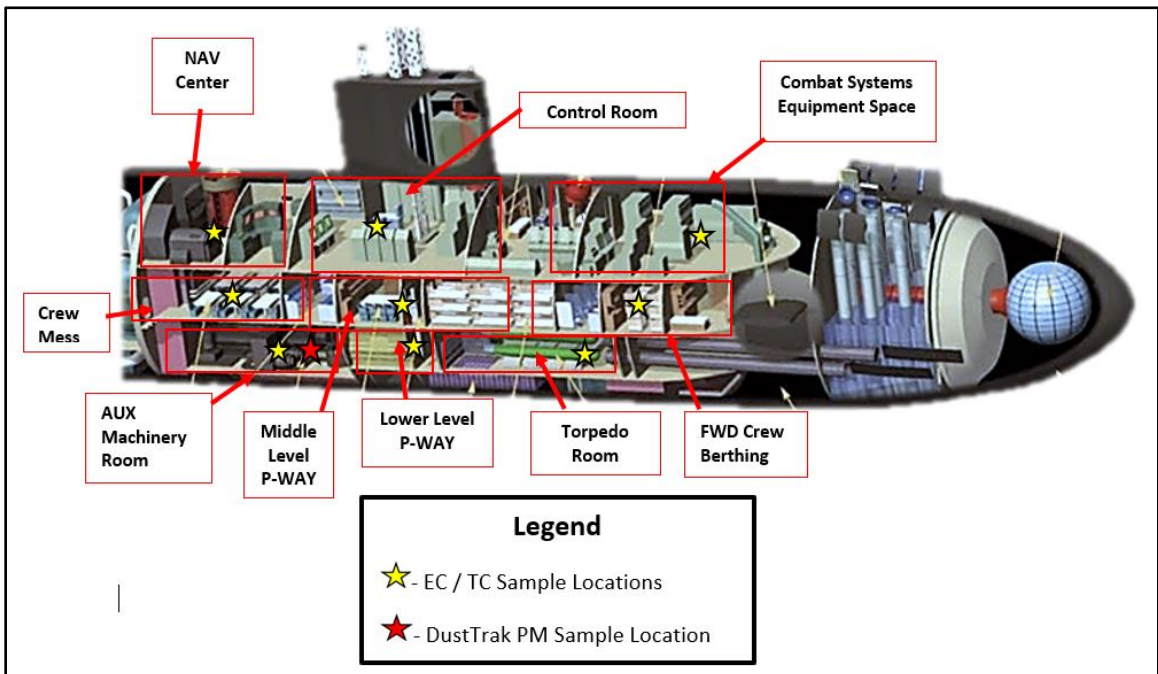


Figure 6: Interior cutaway of LA Class Submarine with sample locations labeled (25)

NIOSH Analytical Method 5040

Method 5040 was published in 1996 in NIOSH Manual of Analytical Methods (NMAM) as way to monitor and quantify EC and TC concentrations as surrogates DE. Personal breathing zone air sampling is typically accomplished using air sampling pumps, at approximately 2-4 L/min flow rate, across 37 mm Quartz-Fiber filters, and in 3-piece cassettes. The quartz-fiber filters are pre-cleaned by baking them in furnaces at 800-900-degree Celsius for 1-2 hours to ensure contamination from OC is removed. Even when stored in closed containers, OC loadings may be present (22). As such, samples require blank correction during laboratory analysis to account for post-bake OC loadings. The limit of detection for this method is $2 \mu\text{g}/\text{m}^3$ for a 960-liter air sample. Reported accuracy for the method is ± 16.7 percent. Total carbon (EC+OC) is determined by this method using thermal-optical-transmittance analyzer (TOA) techniques and flame ionization detector (FID). Figure 7 is a schematic diagram of a TOA.

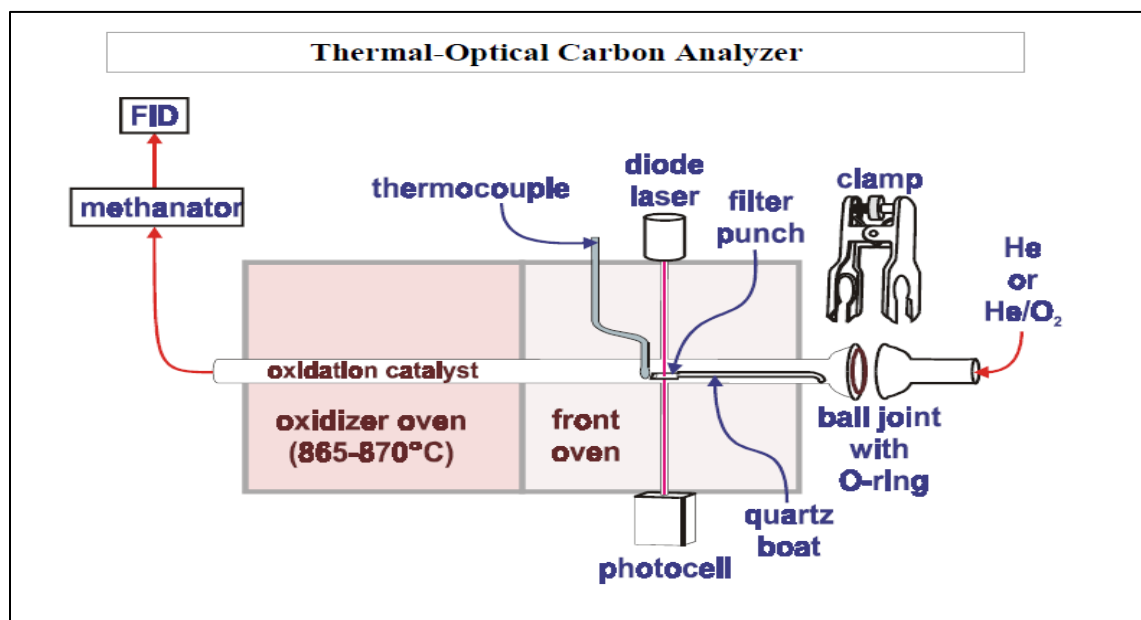


Figure 7: Schematic of a Thermal Optical Analyzer (16)

TOA is used to analyze the TC in fiber filters by pyrolyzing the carbon content of the filter punch. The carbon on the filter is oxidized to carbon dioxide, which is reduced to methane. Finally, the methane is measured using an FID. To utilize this method, a 1.5 cm², representative punch is removed from the sample filter for analysis. The filter punch is placed in a quartz boat placed in the path of a red-light diode laser. The filter punch is baked in a helium atmosphere, with temperature ramps to 900°C. The sample is then cooled to 600°C and oxygen is added. A series of four heating ramps, this time with the sample in an oxidizing atmosphere, then brings the sample to a temperature of 920°C (18). The remaining carbon is burned off during this stage of the analysis. Figure 8 shows a plot of the temperature set points and the gas changes in the TOA oven.

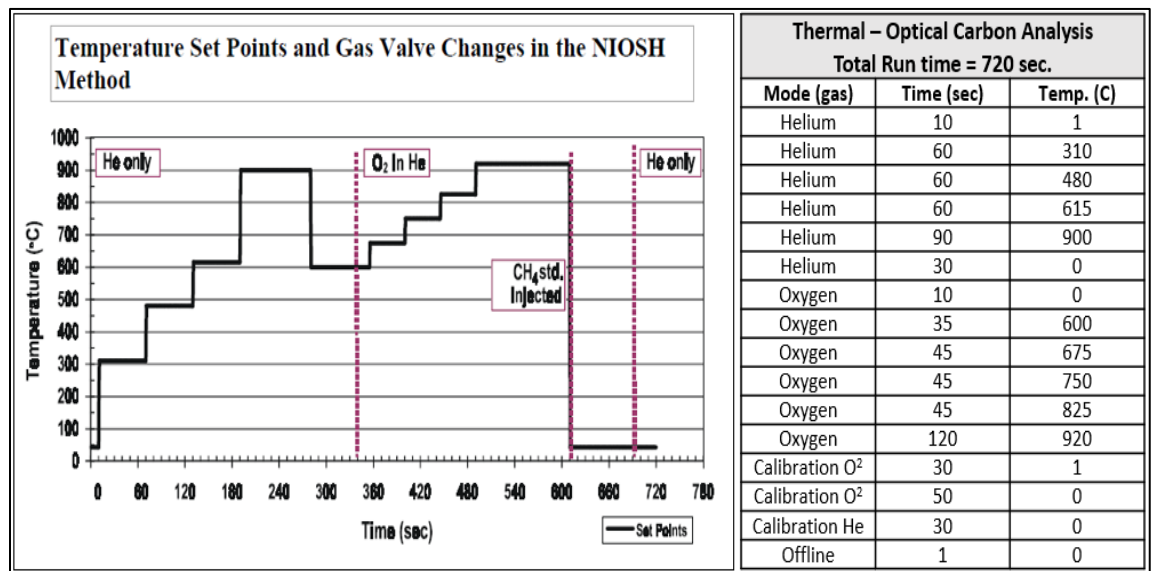


Figure 8: Thermal Optical Analysis Temperature Set Points (16)

Built-in software divides TC into OC and EC by setting the split time between the two as the time in the analysis when the transmittance of the filter returns (after darkening then lightening) to its original value at the beginning of the analysis (18). The EC/TC results ($\mu\text{g}/\text{cm}^2$) is then multiplied by the filter deposit area (typically 8.5 cm² for

a 37-mm filter) for a total mass. The same process is repeated for the blank filter. The final step is to calculate the EC/TC concentration with blank correction, using the following calculation:

$$C_{EC} = \frac{W_{EC} - W_b}{V}$$

Where:

C_{EC} = Concentration of EC ($\mu\text{g}/\text{m}^3$)

W_{EC} = mass found on sample (μg)

W_b = Mass found on blank (μg)

V = Volume of air sampled (Liters)

(22)

Aerosol Monitoring

The DustTrak DRX 8534 was used in this study to characterize the PM mass concentrations and particle size distribution at the security Guard Shack and in the Diesel Operator Booth during snorkeling operations. The DustTrak DRX is a handheld, multi-channel laser photometer aerosol monitor. It allows for real time monitoring of aerosols, dusts, fumes and smoke. The DustTrak simultaneously measures the size segregated mass fraction concentrations corresponding to PM_1 , $\text{PM}_{2.5}$, PM_{resp} , PM_{10} and PM_{Total} size fractions through the use of a photometer and laser diode (35). The aerosol concentration operating range of the DustTrak is $1 \mu\text{g}/\text{m}^3$ to $150 \text{ mg}/\text{m}^3$ (35).

Aerosol is drawn in a continuous stream into the sensing chamber using a diaphragm. Part of that stream is split and filtered through a HEPA filter. This air is injected back into the chamber and used as sheath flow. The remaining sample air enters the sensing chamber where it is illuminated by a sheet of laser light produced by a laser diode. That light then passes through a collimating lens, then a cylindrical lens to form a thin sheet of light (32). A gold coated spherical mirror captures a significant fraction of

the light scattered by the particles and focuses it on to a photodetector (32). The voltage across the photodetector, is proportional to the mass concentration and is used to determine the concentration of the aerosol, while the individual pulses from the photometer are also used to make single particle measurements (32). Figure 8 is a schematic of the internal workings of the DustTrak DRX.

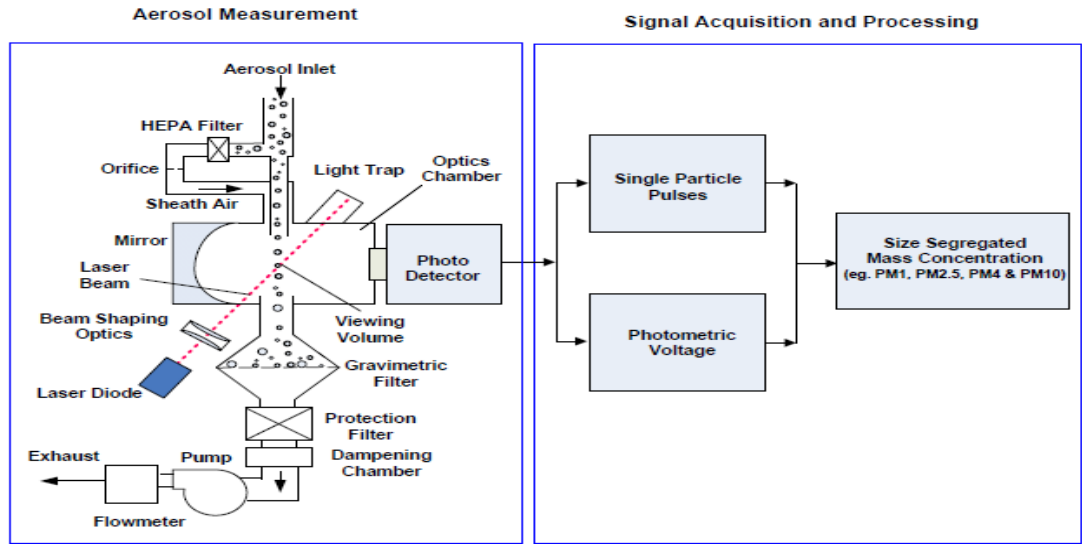


Figure 9: Schematic of DustTrak Aerosol Chamber and Signal Processing Unit (27)

Quality Assurance/Quality Control

All equipment was inspected prior to commencement of sampling to verify operational status and full functionality. The DustTrak and personal sampling pumps were fully charged the day prior to the sampling period. Zero checks for the DustTrak were performed using the Zero Filter in accordance with manufacturer’s user calibration instructions (33). Additionally, the DustTrak internal flow rate (3.0 L/min) was verified using Mesa Labs Defender 510 medium flow primary calibrator. Air sampling pumps were calibrated to a flow rate of 4.0 L/min before sampling using a Mesa Labs Defender 510 medium flow primary calibrator (Mesa Laboratories Inc, Butler, NJ). Post-sampling calibration checks were done to ensure flow rates were within ± 5 percent of the pre-

sampling target flow rate. One blank filter was submitted to the laboratory from each submarine per day of sampling. All samples were blank corrected by the laboratory using the mean EC/TC concentration of the 1.5 cm² filter punch from the blank filter (22).

Time Weighted Average Conversion

EC and TC concentrations were compared to 8-hour TWA OELs as a point of reference, to estimate area airborne exposures during a snorkeling period. The calculation below was used to determine the task TWA in accordance with NMCPHC Industrial Hygiene Field Operations Manual (IHFOM), Chapter 3 (25). Concentrations during any unsampled portion of the work shift were assumed to be equal to the average exposure for all sampled portions of the work shift in accordance with guidance in the IHFOM (25). This assumption is based on the fact that one of the submarines include in this study was already snorkeling prior to arrival of the researcher to the sample location. Another submarine included in this study necessitated the researcher terminate sampling prior to cessation of snorkeling.

$$TWA = \frac{C_1T_1 + C_2T_2 + \dots C_nT_n}{T_1 + T_2 + \dots T_n}$$

Where: C = Concentration of the contaminant in sample

T = time of the exposure period (minutes)

(25)

Censored Data

EC/TC samples below the LOD (2 µg for EC, 4 µg for TC) were treated as censored data following guidance from the IHFOM, Chapter 4 (24). The substituted LOD values were calculated by dividing the LOD by the square root of 2.

Statistical Analysis

Data analysis were calculated using the American Industrial Hygiene Association's IHSTAT (v.235, Falls Church, VA) (4). Descriptive statistics were calculated to determine sample mean, exceedance fraction, and standard deviation for the TWA results. TrakPro™ Version 4.7.1.0 (Shoreview, MN) software was used to download, view, and analyze PM data (34).

CHAPTER 4: Results

EC/TC CONCENTRATIONS OUTSIDE THE SUBMARINE

Submarine 1 EC/TC Results

Table 1 describes the environmental conditions on the day of sampling outside Submarine 1. A total of nine EC and TC area samples were collected outside Submarine 1 in area sampling locations described in Figure 5. Descriptive statistics of the EC/TC samples collected outside Submarine 1 are displayed in Table 2. The mean sample length was 160 minutes. Twenty-two percent (2 of 9) of the samples exceeded the Cal OSHA EC TLV ($20 \mu\text{g}/\text{m}^3$). The mean concentration for all the EC samples collected on Submarine 1 was $10 \mu\text{g}/\text{m}^3$ (standard deviation: $9.31 \mu\text{g}/\text{m}^3$). EC concentrations ranged from 1.41 to $23 \mu\text{g}/\text{m}^3$. Forty-four percent (4 of 9) of the sampled locations exceeded the MSHA TC PEL ($160 \mu\text{g}/\text{m}^3$). The mean concentration for all the TC samples collected outside Submarine 1 was $173 \mu\text{g}/\text{m}^3$ (standard deviation $184 \mu\text{g}/\text{m}^3$). TC concentrations ranged from 2.83 to $401 \mu\text{g}/\text{m}^3$.

Submarine 2 EC/TC Results

Table 1 describes the environmental conditions on the day of sampling outside Submarine 2. A total of nine EC and TC area samples were collected outside Submarine 2 in area sample locations described in Figure 5. Descriptive statistics of the EC/TC samples collected outside Submarine 2 are displayed in Table 2. The mean sample length was 255 minutes. All EC samples were below the LOD. TC was detected in seventy-seven percent (7 of 9) of the filter samples. Concentrations of TC ranged from 2.83 – $23.0 \mu\text{g}/\text{m}^3$. The mean concentration for all the TC samples collected outside Submarine

2 was $11.3 \mu\text{g}/\text{m}^3$ (standard deviation: $5.94 \mu\text{g}/\text{m}^3$). All TC samples were below the MSHA PEL ($160 \mu\text{g}/\text{m}^3$).

EC/TC CONCENTRATIONS INSIDE THE SUBMARINE

Submarine 3 EC/TC Results

Table 1 describes the environmental conditions on the day of sampling outside Submarine 3. A total of nine EC and TC area samples were collected inside Submarine 3 in area sampling locations described in Figure 6. Descriptive statistics of the EC/TC samples collected inside Submarine 3 are displayed in Table 2. Mean sample length was 253 minutes. Sixty-seven percent (6 of 9) of the EC samples exceeded the Cal OSHA EC TLV ($20 \mu\text{g}/\text{m}^3$). The mean concentration of all the EC samples collected inside Submarine 3 was $23.4 \mu\text{g}/\text{m}^3$ (standard deviation: $6.27 \mu\text{g}/\text{m}^3$). EC concentrations ranged from $15 - 32 \mu\text{g}/\text{m}^3$. One hundred percent (9 of 9) of the TC samples exceeded the MSHA TC PEL ($160 \mu\text{g}/\text{m}^3$). The mean concentration for all the TC samples collected inside Submarine 3 was $617.8 \mu\text{g}/\text{m}^3$ (standard deviation $198 \mu\text{g}/\text{m}^3$). TC concentrations ranged from the 390 to $1,000 \mu\text{g}/\text{m}^3$.

Table 1: Environmental Conditions Outside Submarine 1-3

Environmental Conditions				
Location	Temperature (F)	Humidity (%)	Barometric Pressure (in Hg)	Wind Speed & Direction (MPH)
Submarine 1	76	85	30	1, SW
Submarine 2	63	39.3	30.2	2, SE
Submarine 3	51	47	30	20, S

Table 2: Descriptive Statistics for Ambient and Internal EC/TC samples

Ambient EC/TC Concentration										
Location	N	Mean Sample Length (min.)	Mean EC Conc. ($\mu\text{g}/\text{m}^3$)	Standard Deviation ($\mu\text{g}/\text{m}^3$)	EC Range ($\mu\text{g}/\text{m}^3$)	Percent > Cal OSHA EC TLV (20 $\mu\text{g}/\text{m}^3$)	Mean TC Conc. ($\mu\text{g}/\text{m}^3$)	Standard Deviation ($\mu\text{g}/\text{m}^3$)	TC Range ($\mu\text{g}/\text{m}^3$)	Percent > MSHA TC OEL (160 $\mu\text{g}/\text{m}^3$)
Submarine 1	9	160	10	9.31	1.41 - 23	22%	172.8	184	2.83 - 410	44%
Submarine 2	9	255	*1.41	0	*1.41	None	11.04	5.94	2.83 - 23	None
Internal EC/TC Concentration										
Submarine 3	9	253	23.4	6.27	15 - 32	67%	617.8	198	390 - 1000	100%

* Denotes samples that were below the EC Limit of Detection Submarine 2

DISTANCE FROM DIESEL EXHAUST PORTS

Submarine 1 EC/TC Results

Wind speed and direction were 1 MPH in a southwest direction on the day of sampling (Table 1). All area samples ($n = 5$) within 50-feet of the starboard exhaust port for Submarine 1 had detectable levels of EC and TC (Figure 10). The mean EC concentration within this distance was $16.96 \mu\text{g}/\text{m}^3$ (standard deviation = 6.25). The range of EC concentrations was $6.8 - 23 \mu\text{g}/\text{m}^3$. Forty percent of the EC samples exceeded the Cal OSHA EC TLV ($20 \mu\text{g}/\text{m}^3$). The mean TC concentration at this distance was $308.8 \mu\text{g}/\text{m}^3$ (standard deviation = 124). The range of TC concentrations was $94 - 410 \mu\text{g}/\text{m}^3$. Eighty percent of the TC samples exceeded the MSHA TC PEL ($160 \mu\text{g}/\text{m}^3$). The highest EC/TC concentrations, 23 and $410 \mu\text{g}/\text{m}^3$, respectively, were observed at the Pier 2 sample location. EC/TC concentrations inside the Guard Shack were 17 and $370 \mu\text{g}/\text{m}^3$, respectively.

Submarine 2 EC/TC Results

Wind speed and direction were 2 MPH in a southeast direction on the day of sampling (Table 1). All EC samples, regardless of distance from the diesel exhaust ports were below the LOD. TC was detected in eight of the nine area samples. These finding may be reflective of organic carbon interferences produced by other shipyard operations such as forklifts, maritime vessels, and painting activities in the areas adjacent to Submarine 2.

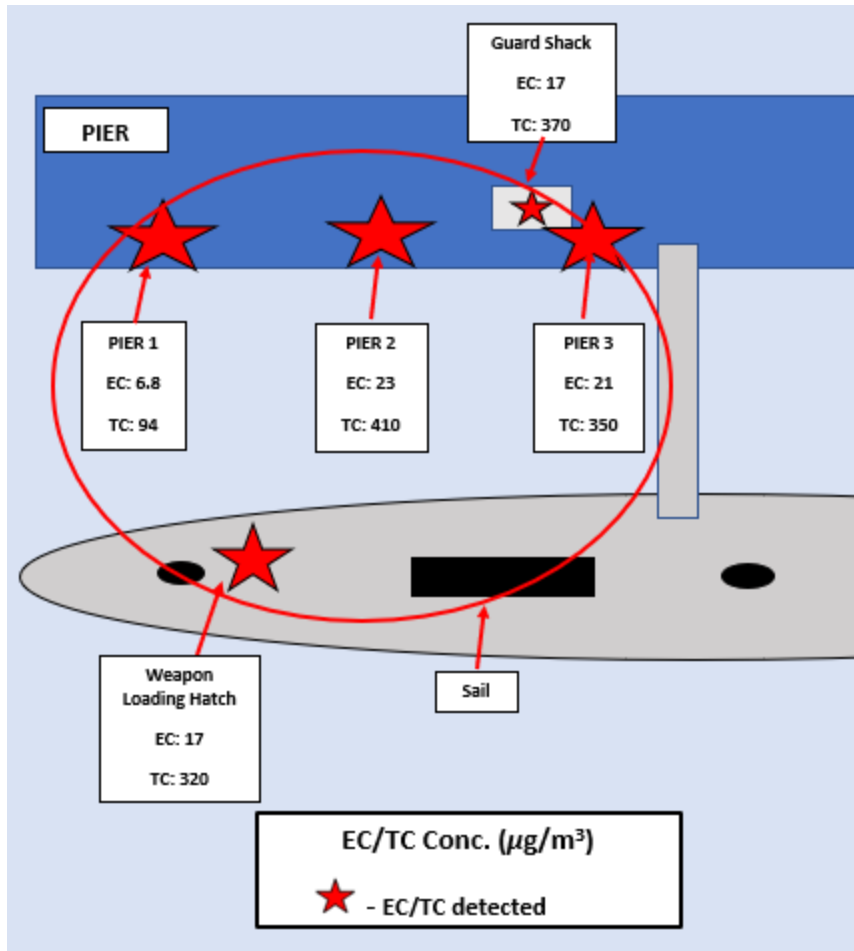


Figure 10: EC/TC Concentrations Within 50-feet from the Starboard Exhaust Port

EC/TC CONCENTRATIONS BY LEVEL IN SUBMARINE 3 FORWARD COMPARTMENT

A total of three area EC/TC samples were collected on each level in the Forward Compartment inside Submarine 3 ($n = 9$) in locations shown in Figure 6. Descriptive statistics were used to compare results of measurements taken on each level. Table 3 is a summary of mean EC/TC concentrations measured on each level. Mean EC/TC concentrations were highest in the forward compartment lower level: 28.7 and 787 µg/m³, respectively. The mean EC concentration in the forward compartment middle and lower level exceeded the Cal OSHA EC TLV (20 µg/m³). The mean TC concentration on each level exceeded the MSHA TC PEL (160 µg/m³).

Table 3: Submarine 3 Upper, Middle, and Lower Level EC/TC Concentrations

Task TWAs					
	N	Mean EC ($\mu\text{g}/\text{m}^3$)	Standard Deviation ($\mu\text{g}/\text{m}^3$)	Mean TC ($\mu\text{g}/\text{m}^3$)	Standard Deviation ($\mu\text{g}/\text{m}^3$)
Upper Level	3	18	3.61	467	108
Middle Level	3	23.7	6.81	600	167
Lower Level	3	28.7	3.51	787	198

SUBMARINE PM CONCENTRATIONS

Submarine 1

PM₁₀, PM_{2.5}, and PM_{RESP} concentrations were monitored outside the guard shack on Submarine 1 for three hours using a DustTrak aerosol monitor. Table 4 displays the descriptive statistics of PM concentrations from Submarine 1. The measured PM₁₀, PM_{2.5}, and PM_{RESP} concentrations were 6,530, 4,180, and 4,940 $\mu\text{g}/\text{m}^3$, (std. deviation: 14,761, 9,524, and 11,133) respectively. The range of PM₁₀, PM_{2.5}, and PM_{RESP} concentrations were 30 – 83,900, 27 – 54,600, and 28 – 61,500 $\mu\text{g}/\text{m}^3$, respectively. PM_{RESP} concentrations, 4,940 $\mu\text{g}/\text{m}^3$, exceeded ACGIH recommended TLV (3,000 $\mu\text{g}/\text{m}^3$) for Particles not Otherwise Specified (PNOS).

Submarine 2

PM₁₀, PM_{2.5}, and PM_{RESP} concentrations were monitored outside Submarine 2 in a location where the Guard Shack is usually placed for four hours using a DustTrak aerosol monitor. Table 4 displays the descriptive statistics of PM concentrations from Submarine 2. The measured PM₁₀, PM_{2.5}, and PM_{RESP} concentrations were 19, 16, and

17 $\mu\text{g}/\text{m}^3$, (std. deviation 32, 28, and 29) respectively. The range of PM₁₀, PM_{2.5}, and PM_{RESP} concentrations were 4 – 299, 4 – 300, and 4 – 300 $\mu\text{g}/\text{m}^3$, respectively.

Submarine 3

PM₁₀, PM_{2.5}, and PM_{RESP} concentrations were monitored inside the Diesel Operator’s Booth, in the Auxiliary Machinery Room in Submarine 3 for five hours using a DustTrak aerosol monitor. Table 4 displays the descriptive statistics of PM concentrations from Submarine 3. The measured PM₁₀, PM_{2.5}, and PM_{RESP} concentrations were 1,340, 852, and 855, (std. deviation: 1,249, 1,242, and 1,245) respectively. The range of PM₁₀, PM_{2.5}, and PM_{RESP} concentrations were 11 – 6,720, 11 – 6,730, and 11 – 6,720 $\mu\text{g}/\text{m}^3$, respectively.

Table 4: Descriptive Statistics of PM₁₀, PM_{2.5}, PM_{RESP} for Submarine 1, 2, and 3

Submarine PM Results						
Location	TWA ($\mu\text{g}/\text{m}^3$)	Standard Deviation ($\mu\text{g}/\text{m}^3$)	Background ($\mu\text{g}/\text{m}^3$)	Min ($\mu\text{g}/\text{m}^3$)	Max ($\mu\text{g}/\text{m}^3$)	Sample Length (min.)
Sub 1	PM ₁₀ = 6,530	14,761	30	30	83,900	183
	PM _{2.5} = 4,180	9,524	27	27	54,600	
	PM _{RESP} = 4,940	11,133	28	28	61,500	
Sub 2	PM ₁₀ = 19	32	4	4	299	243
	PM _{2.5} = 16	28	4	4	300	
	PM _{RESP} = 17	29	4	4	300	
Sub 3	PM ₁₀ = 1,340	1,249	11	11	6,720	308
	PM _{2.5} = 1,330	1,242	11	11	6,730	
	PM _{RESP} = 1,330	1,245	11	11	6,720	

CHAPTER 5: Discussion

DE CONCENTRATIONS DURING SNORKELING

The purpose of this investigation was to characterize the surrogates of exposure to DE during pier side snorkeling operations. Area air samples were collected outside two and inside one Los Angeles class submarines in areas representative of the topside footprint and forward compartment where personnel worked and stood security watches. Snorkeling operations vary in length as indicated by the three submarines surveyed in this study.

Submarine 1

Submarine 1 was operating the Emergency Diesel Engine in preparation for a transit to a floating drydock in Submarine Base New London, Groton, CT. As such, air sampling was terminated sooner than the targeted four-hour sample period. All sampling equipment had to be removed prior to the transit. However, the diesel engine was run continuously, in excess of eight hours, while the submarine was towed by tugboats to a nearby floating drydock and during docking procedures. Therefore, the EC, TC, and PM concentrations observed in this study may not reflect true 8-hour concentrations.

Wind speed on the morning of sampling was 1 mile per hour (MPH) in a southwest direction. Five area samples collected downwind of the diesel exhaust ports had detectable levels of EC/TC. These samples were collected within a 50-foot distance from the diesel exhaust port (Figure 9). The DE plume was clearly visible during the sampling period as indicated in Figure 11. The Guard Shack is also located pier-side, adjacent to the submarine sail. Four of the samples did not yield detectable levels of EC/TC. Each of these samples were upwind of the diesel exhaust ports on the port and

starboard side of the sail. These results suggest that there may be an inverse relationship between distance and DE concentrations outside the submarine.



Figure 11: Pier-side Submarine 1 outside of the Guard Shack

EC concentrations within the Guard Shack were $17 \mu\text{g}/\text{m}^3$. Watch standers usually leave the door and windows open to allow airflow (Figure 11). Mean pier-side EC concentrations ($17 \mu\text{g}/\text{m}^3$) measured in this study were similar to those collected in a study conducted by Gan et al., which measured pier-side DE concentrations from Australian submarines downwind from the diesel exhaust ports. The pier-side EC concentrations observed in this study are also comparable to DE concentrations observed in other industries. One study, which measured DE exposure to workers during gas extraction and fracking operations, measured average area EC concentrations $16.9 \mu\text{g}/\text{m}^3$ in proximity of large diesel powered pumps and drilling stations (11). A literature review

on occupational exposure to diesel exhaust found that for maintenance workers of on-road and railroad equipment, distribution workers, fire fighters, and ship dock workers, EC exposure levels generally ranged from LOD to $50 \mu\text{g}/\text{m}^3$ (27).



Figure 12: Submarine 1 Guard Shack

Mean TC concentrations were consistently higher than concentrations of EC from each sample. This disparity may be due to fact that diesel engines burn fuel more efficiently when under load. High TC concentrations, relative to EC, are indicative of the presence of hydrocarbons, primarily from unburned diesel fuel and lubricating oils. The samples collected in this study suggest that DE concentrations may exceed recommended exposure limits outside the submarine during snorkeling operations.

Submarine 2

Submarine 2 was undergoing a deactivation from active service in the submarine fleet. Extensive modification had been done to the submarine to include a complete reconstruction of the sail structure. Due to these extensive modifications, Submarine 2 is not representative of operational Los Angeles class submarines. Figure 12 is a side-by-side view of the modified sail of Submarine 2 next to the typical Los Angeles class sail. The modified sail structure channels the DE upwards, like a chimney on a house, directly to the atmosphere rather than exhausting DE from the side of the sail. Due to these modifications, DE was directed away from sample locations (Figure 14). EC was not detectable in the nine sample locations. While TC was detected, it was potentially due to OC from other sources of interference present in the area, such work trucks, forklifts, and other maritime sources.



Figure 13: Submarine 2 Modified Sail vs. Submarine 1 Normal Sail



Figure 14: Submarine 2 Exhaust Plume from Modified Sail

Submarine 3

Submarine 3 was operating its Emergency Diesel Engine as a part of a performance certification on the day of sampling. Pier-side area samples were not collected due to wind speeds in excess of 25 MPH. External samples were likely to have been at or below the limit of detection due to the excessive wind speeds. Additionally, the diesel exhaust ports were obstructed by scaffolding enclosed in plastic wrap to support sandblasting activities (Figure 16). The plastic wrap and wind conditions may have contributed to the recirculation of DE within the submarine.

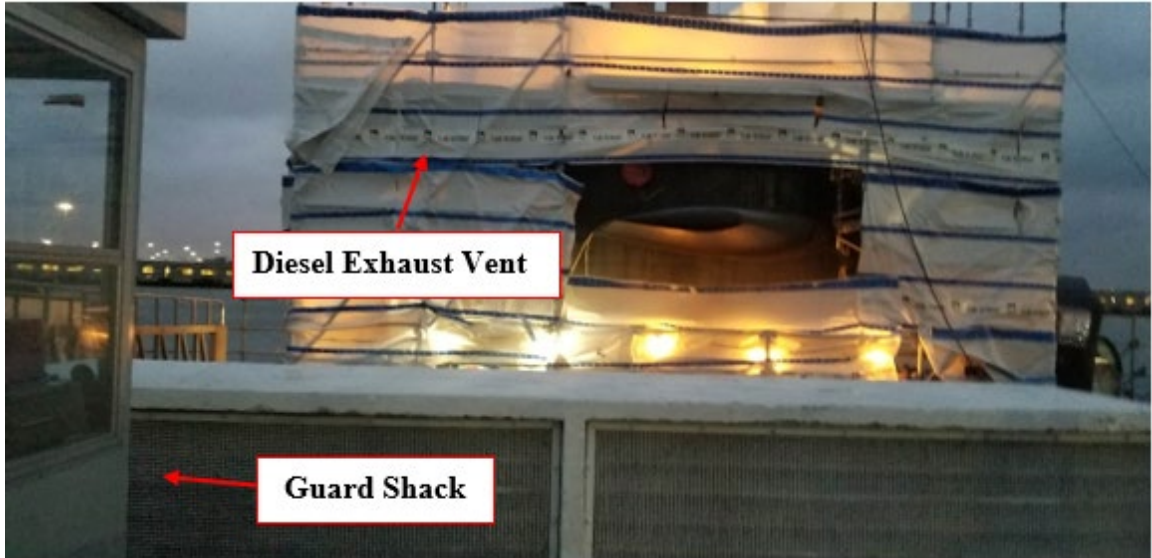


Figure 15: Submarine 3. DE Exhaust Vents Obstructed by Scaffolding

Mean EC and TC concentrations were highest in the lower level of the forward compartment, 29 and 786 $\mu\text{g}/\text{m}^3$, respectively. The emergency diesel engine is in the AMR in the forward compartment lower level. These observations suggest that there is significant leakage of DE from the diesel engine's piping and ducting. The area sample collected in the AMR was the highest observed concentration inside Submarine 3 with EC and TC concentrations of 32 and 1,000 $\mu\text{g}/\text{m}^3$, respectively. Gan et al., similarly, saw the highest DE concentrations in the engine room on Australian submarines (12).

EC and TC concentrations were highest in the Forward Crews Berthing in the middle level: 29 and 750 $\mu\text{g}/\text{m}^3$, respectively. Upper level concentrations measured highest in the Navigation Center: 22 and 590 $\mu\text{g}/\text{m}^3$, respectively. DE concentrations were highest in workspaces that were most distant furthest from entrance/egress hatches. This observation suggests that DE may accumulate in those spaces during snorkeling. DE concentrations throughout the submarine suggest exposure limits may be exceeded inside the submarine during snorkeling operations. Diesel engine operators are at the

highest risk of exposure to DE during snorkeling operations. All personnel inside the submarine may be at risk of DE exposure during snorkeling, if the area samples collected during this study are indicative of personal exposure.

PM CONCENTRATIONS DURING SNORKELING

PM₁₀, PM_{2.5}, and PM_{RESP} were higher outside the submarine than inside the submarine when measured with a DuskTrak aerosol monitor. DE measurements taken outside of the submarine may contain salt and organic materials from the sea water used as coolant in the exhaust plenum, unburned fuel, and lubricating oils. The DustTrak segregates particles by size but is unable to segregate particles by species which may explain why PM concentrations were higher outside than inside the submarine. The PM concentrations observed both topside and inside Submarine 1 & 3 may induce irritation of the eyes, nose, and throat in individuals.

STUDY LIMITATIONS

There were several limitations of this study. Area monitoring conducted during this study may not be representative of personal exposures. While area monitoring is not used to determine a worker's exposure, it can be useful in assessing whether control measure are warranted. Area sampling was used in this study as a tool to perform a basic characterization of DE during snorkeling. Multiple personal samples across similar exposure groups would adequately determine DE exposures on submarines while the Emergency Diesel Engine is running.

Another limitation of this study is its limited sample size. Convenience sampling was used to select submarines that would be snorkeling. Only three Los Angeles class

submarines were available for sampling during the time-period. Collecting samples from more operational submarines was not possible due to unavailability and operational requirements during the sampling period.

Sample duration is a limitation of this study. Concentrations during unsampled portions of the work shift were assumed to be equal to the averaged measured concentrations. This is a conservative measure of exposure which is intentionally biased toward protection of personnel.

Area samples were not collected inside Submarine 1 and 2 and outside of Submarine 3. As a result, it is assumed that DE area concentrations outside Submarine 1 and inside Submarine are representative of concentrations from other Los Angeles class submarines.

CHAPTER 6: Conclusions

Measurements collected in this study suggested that submariners may be exposed to DE concentrations that exceed exposure limits during snorkeling operations. EC and TC concentrations exceeded exposure limits, both outside and inside the submarine while the Emergency Diesel Engine was running. This study observed an inverse relationship between EC/TC concentration and distance from diesel exhaust ports. The findings of this study also suggest DE concentrations are highest in the lower level and lowest in the upper level of the submarine while snorkeling. These findings suggesting the DE leakage occurs in the Auxiliary Machinery Room and that DE is recirculated through the ventilation system. The results of this study suggest that ventilation within the submarine may not provide adequate dilution ventilation while the Emergency Diesel Engine is in use.

Future studies should collect air samples in the personal breathing zone for EC/TC from personnel on submarines during snorkeling operations to adequately characterize personal exposures. Future studies should also be done to characterize the DE emissions during snorkeling operations on Ohio, Virginia, Seawolf, and additional LA Class submarines to adequately measure DE emission and to determine whether OELs are exceeded during snorkeling operations.

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Appendix A

IHFOM INDUSTRIAL HYGIENE AIR SAMPLING SURVEY FORM

INDUSTRIAL HYGIENE AIR SAMPLE SURVEY FORM Sample Date: _____

SHIP NAME : _____ Hull#: _____ Squadron: _____						
Pier#: _____						
POC Name: _____						
POC Phone: _____						
POC Email: _____						
Start Time: _____			Stop Time: _____			
PUMP Number	Serial #	PUMP MFG / Model	Pre-Cal Flow Rate (lpm)	Post-Cal Flow Rate (lpm)	% Error [(Pre - post) / (post)] *100	Sample ID - Run Time - Total Volume
1						
2						
3						
4						
5						
6						
7						
8						
9						
Calibrator Mfg. / Model / Serial Number			_____			
Temp (F): _____		Humidity: _____		Barometric Pressure (inHg): _____		
Wind Speed: (MPH) _____		Wind Direction: _____				

Appendix B

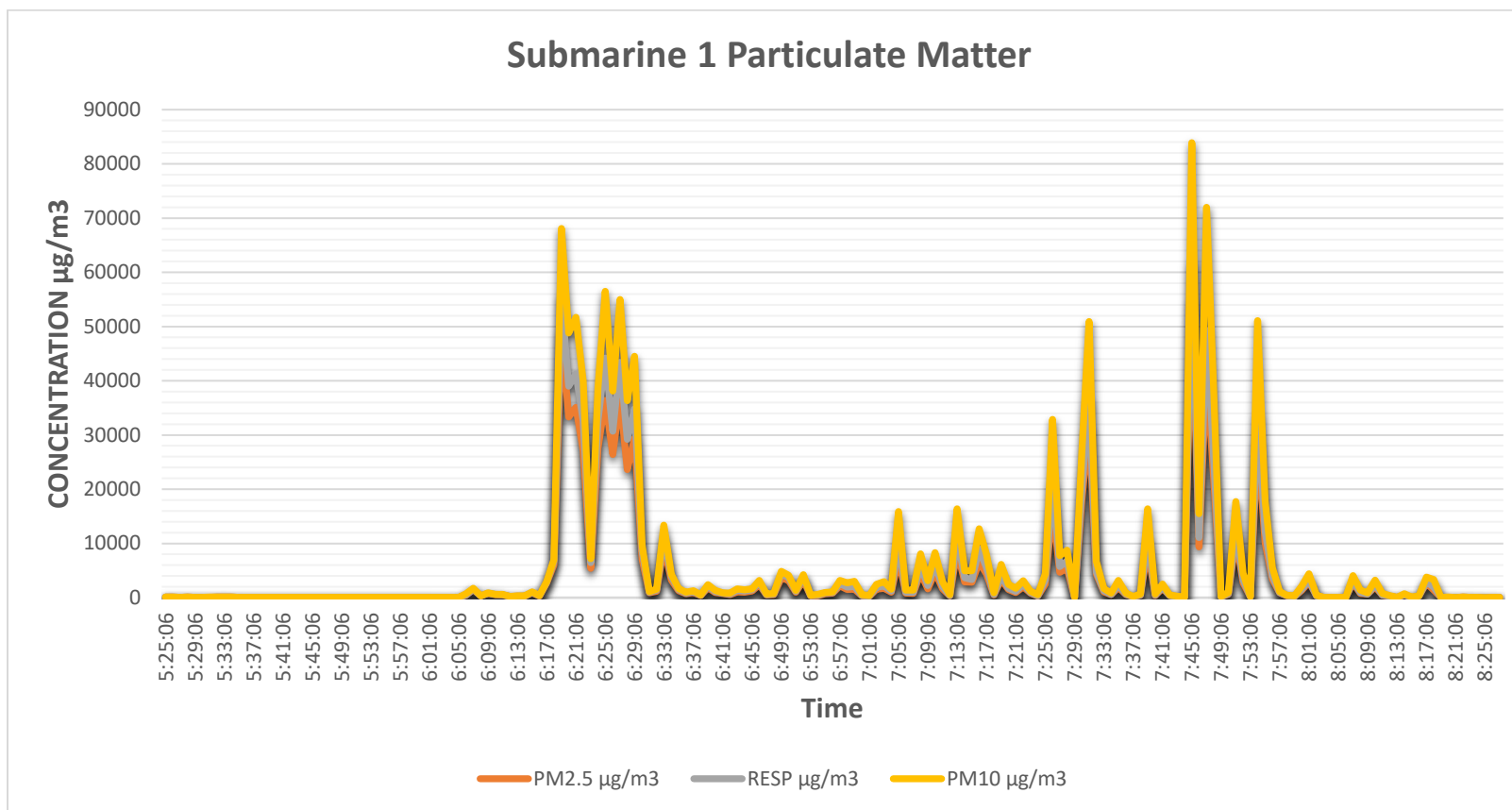
AREA SAMPLES RAW DATA

	EC (µg) [MASS]	EC (µg/m3) [CONC]	OC (µg) [MASS]	OC (µg/m3) [CONC]	TC (µg) [MASS]	TC (µg/m3) [CONC]
SUBMARINE 1						
Pier 1	4.8	6.8	64	87	69	94
Pier 2	17	23	290	390	300	410
Pier 3	16	21	250	330	260	350
Pier 4	1.41	1.41	2.83	2.83	2.83	2.83
Guard Shack	13	17	260	350	270	370
Weapon Loading Hatch	8.9	17	160	300	170	320
FWD Escape Hatch	1.41	1.41	2.83	2.83	2.83	2.83
AFT Escape Hatch	1.41	1.41	2.83	2.83	2.83	2.83
Jack Staff	1.41	1.41	2.83	2.83	2.83	2.83
SUBMARINE 2						
Pier 1	1.41	1.41	12	12	12	12
Pier 2 (Brow)	1.41	1.41	14	14	14	14
Pier 3	1.41	1.41	14	14	14	14
Pier 4	1.41	1.41	11	11	11	11
AFT Guard Shack	1.41	1.41	23	23	23	23
Weapon Loading Hatch	1.41	1.41	6.7	6.7	6.7	6.7
Pier 5	1.41	1.41	2.83	2.83	2.83	2.83
AFT Escape Hatch	1.41	1.41	13	13	13	13
Jack Staff	1.41	1.41	2.83	2.83	2.83	4

SUBMARINE 3						
CSES	16	15	400	370	410	390
Control Room	18	17	420	400	440	420
NAV Center	23	22	590	560	610	590
FWD Berthing	29	29	720	720	750	750
MDL LVL P-WAY	26	26	600	610	630	630
Crew's Mess	16	16	400	400	420	420
Torpedo Room	25	25	580	580	610	610
Lower Level P-WAY	29	29	730	730	750	750
AMR	32	32	1000	1000	1000	1000

Appendix C

SUBMARINE PARTICULATE MATTER GRAPH



Submarine 3 Particulate Matter

